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Multiuser MIMO Channel Measurements and Performance in a Large Office Environment

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***Abstract*— We consider a multiuser MIMO-OFDMA scheme which exploits multiuser diversity in all dimensions: time, frequency and space. The main contribution of this paper is the evaluation and explanation of multiuser MIMO in a real world scenario, i.e. a large office room, based on measured channels. We report interesting results of a measurement campaign which suggest that significant MIMO gains are possible in an indoor environment even under strong line-of-sight condition as long as the distance of the users from the base station is larger than a reverberation distance which only depends on room surface and material. We show results on the achievable multiuser MIMO data rates for the given scenario, compare to theoretical limits and discuss the results in the light of the insights gained from the measurement campaign. We also introduce restrictions on the rate distribution between users, i.e. QoS constraints. It is shown that the theoretical limits can be approximately achieved provided that the users which compete for the spatial resources are carefully chosen.**

I. Introduction

Future wireless broadband systems will rely on multicarrier transmission such as orthogonal frequency division multiplex (OFDM) in combination with multiple antenna technologies (multiple-input multiple-output, MIMO) in order to obtain high spectral efficiency. Moreover, channel knowledge at the transmitter which can be obtained from channel estimation in the uplink signal in a time division duplex (TDD) system or through a feedback channel receives increasing attention.

In particular, channel knowledge at the transmitter allows to exploit multiuser diversity, i.e., a particular subcarrier is allocated to the user with the highest instantaneous SNR. Given that the channel is time-varying, on the average all users benefit and the sum capacity of the system can be significantly increased. The price to pay is that a certain user may not be scheduled for some time during which other users are in a better channel state. This may be a disadvantage in delay sensitive applications.

Given sufficient scattering, a MIMO system offers another dimension to be included in the scheduling process, i.e. the spatial domain. Three scheduling options are depicted in Figure 1. While static orthogonal frequency division multiple access (OFDMA) is fair in the sense that it allocates the same amount of resources in time, frequency and space to each user, dynamic OFDMA gives a subcarrier to the user with the highest SNR. However, the spatial dimension is not taken into account, i.e. all spatial dimensions on a subcarrier are allocated to the same user.

Our proposed algorithm CZF-SESAM (cooperative zero forcing - successive encoding successive allocation method), which will be explained later, includes the spatial domain into the scheduling process. This is particularly promising in systems, where the transmitter is equipped with more antennas than the receivers, which is a reasonable assumption for the downlink of a cellular system. The number of spatial dimensions which can be exploited per subcarrier is limited by the minimum of transmit and receive antennas. Hence, the terminals are the limiting factors. Given a large number of users, by assigning different spatial dimensions on the same subcarrier to different users, the number of spatial dimensions which can be exploited is not any more limited by the number of antennas per terminal but rather by the number of antennas at the base station. However, it becomes more difficult to resolve spatial interference if the receive antennas belong to different users and, hence, cannot cooperate. This problem is addressed in our proposed algorithm CZF-SESAM.

In this paper, we give an illustrative explanation of the principle idea of CZF-SESAM. For mathematical details we refer to [1] – [5]. The main contribution of this paper is the evaluation and explanation of multiuser MIMO in a particular scenario, i.e. a large office room, with measured channels. We report interesting results of a measurement campaign which suggest that significant MIMO gains are possible in an indoor environment even under strong line-of-sight condition as long as the distance of the users from the base station is larger than a room-dependent reverberation distance. We show results on the achievable data rates for the given scenario, compare to theoretical limits and discuss the results in the light of the insights gained from the measurement campaign. We also introduce restrictions on the rate distribution between users, i.e. QoS constraints. It is shown that the theoretical limits can be approximately achieved provided that the users which compete for the spatial resources are carefully chosen.

II. Channel Measurements and Interpretation

We performed multiuser MIMO channel measurements in a large office environment at Aalborg University, Denmark. The floor plan is depicted in Figure 2. For the measurements, we

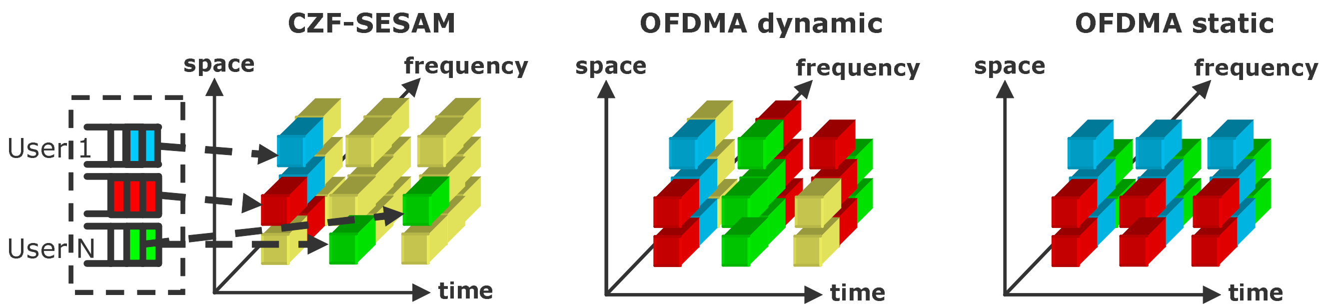

Fig. 1. Scheduling options in MIMO-OFDMA.

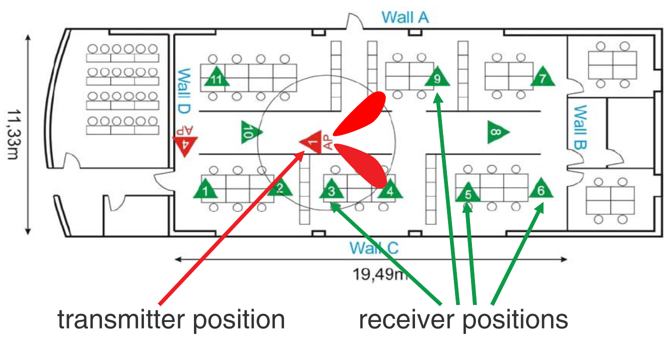

Fig. 2. Floorplan for channel measurement campaign.

Fig. 3. Transmitter (left) and receiver (right).

used the Tx antenna array shown on the left hand side in Figure 3 with 4×4 active elements surrounded by two rows of dummy elements in order to make mutual coupling effects identical for all elements. The transmitter was mounted at position AP1 (see Figure 2) at the ceiling with the monopoles looking downwards with main beam into -45^0 elevation. Similarly, as receivers we used an array with 8×4 active elements and monopoles looking upwards with main beam into $+45^0$ elevation as shown on the right hand side in Figure 3. The receivers were mounted on desk level and could be moved along a track. The receiver positions are marked in Figure 2 with arrows and numbers 1-11. It should be noted that no measurement data is available for position 10. Hence, 10 users compete for the available resources.

A correlation sounder with 5.8GHz center frequency, 100 MHz bandwidth and a total transmit power of 16 W was used. The transmitter was equipped with 16 separate transmitters whereas at the receiver 4 Rx chains with multiplexer formed in total 32 Rx channels. Although the channels from AP1 to the individual receiver positions are measured separately, they can be considered simultaneous since changes to the environment during the measurements were kept to a minimum.

In the following, we will highlight only a few aspects which are important in the context of multiuser MIMO. For details on the measurement campaign, we refer to [6] – [8].

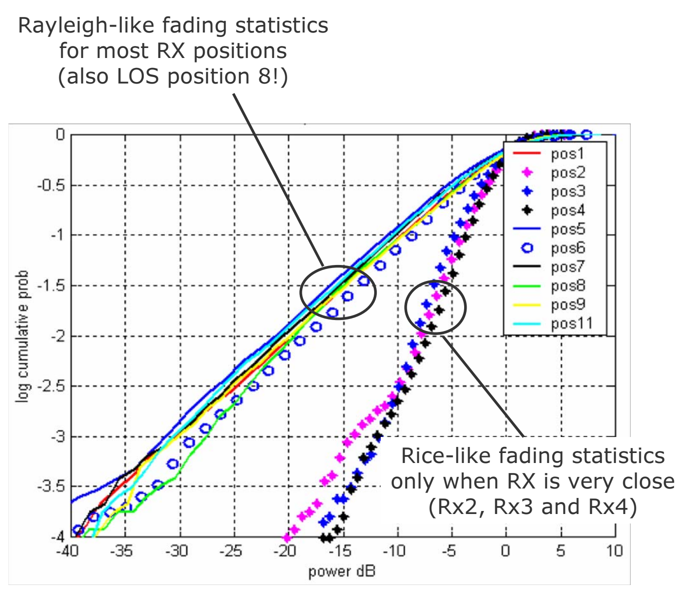

Fig. 4. Fading statistics for different receiver positions.

First, we consider the fading statistics at different positions in the room. Figure 4 shows the logarithmic cumulative probability versus the received power. An interesting observation is that almost all receiver positions face Rayleigh fading. This

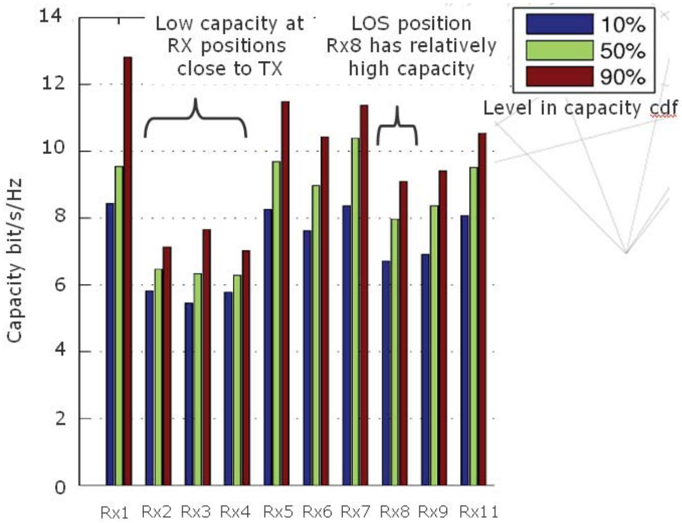

Fig. 5. Outage capacity at different receiver positions. SNR = 10 dB.

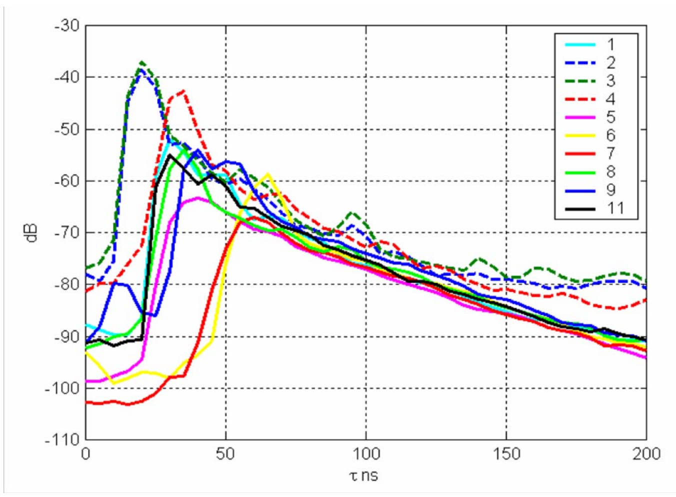

Fig. 6. Power delay profile at different receiver positions normalized to back-to-back level (0 dB).

is true even for line-of-sight (LOS) positions such as receiver 8. Rician fading is only observed for the receiver positions 2-4 which are very close to the transmitter.

Since Rayleigh fading usually comes along with low spatial correlation and consequently high channel rank, we may conclude that high MIMO gains can be exploited in such an indoor scenario even under LOS condition. This is confirmed in the capacity results depicted in Figure 5. Here, the 10%, 50% and 90% outage capacity is shown for a normalized received SNR of 10 dB at all receiver positions. Relatively low capacity is observed for the positions with Rician fading whereas the other positions show relatively high capacity no matter if there is LOS. Of course, for a given transmit power, the receiver positions close to the access point will have a higher SNR. However, the results in Figure 5 indicate that spatial multiplexing (MIMO) gains can be exploited at all receiver positions except for those very close to the access point.

Figure 6 shows the power delay profiles at different receiver positions. We observe a strong direct path for receiver positions close to the transmitter (dashed lines). All receiver positions show the well known exponential decay. However, the important observation is that the decay is constant and that the tails of the power delay profiles for all receiver positions overlap strongly. This observation lead us to a channel model which is strongly related to acoustics (for details see [6]). In acoustics, it is known that diffuse scattering leads to a uniformly distributed diffuse field. The distance from the transmitter at which the diffuse field starts to dominate the direct field is called the reverberation distance. Using a theory in analogy with acoustics, we derived an equation for the reverberation distance r_d of electromagnetic waves [6]:

$$r_d = \frac{1}{4}\sqrt{\frac{D_1 D_2, \eta A}{\pi}}, \tag{1}$$

where D_1 and D_2 are the directivities of transmit and receive antenna, respectively. A is the surface of the room and η is the absorption coefficient which is determined by lossy walls and other objects of absorption in the room. We have indicated the computed reverberation distance in Figure 2 as a circle around the access point. It can be seen that the receivers 2-4, which show Rician fading and low MIMO capacity, are close to the reverberation distance.

The important implications for the application of MIMO in indoor scenarios are as follows: For a given room, we can compute a reverberation distance r_d. For distances larger than r_d, the channel is spatially approximately uncorrelated. Even in case of LOS, a high MIMO capacity can be achieved. Consequently, MIMO will be effective in indoor environments as long as the distance of the receiver to the access point is larger than the reverberation distance no matter if there is LOS or not.

III. Principle of CZF-SESAM

If the instantaneous channel matrix $\mathbf{H}$ of a MIMO channel is known, the best thing to do is diagonalization of the channel using a singular value decomposition (SVD) [9]: The transmitter multiplies the transmit signal with the right singular vectors of the channel matrix H, the receiver multiplies with the left singular vectors. With n_T transmit and n_R receive antennas, this yields $\min\{n_T, n_R\}$ decoupled channels which we refer to as spatial dimensions. As stated in the introduction, in multiuser MIMO, the receive antennas may belong to different users which cannot cooperate. Hence, a singular value decomposition of the total multiuser channel cannot be computed at the receiver. I.e., the channel cannot be decoupled and inter-user interference occurs. Our proposed algorithm CZF-SESAM (cooperative zero forcing - successive encoding successive allocation method), which will be described in the sequel, avoids inter-user interference by means of signal processing at the transmitter.

In order to avoid interference between the spatial dimensions of different users, CZF-SESAM applies successive encoding where each beam (spatial dimension) lies in the null space of previously allocated beams and interference of previously allocated beams is cancelled at the transmitter by means of dirty paper coding [10] which can be implemented as Tomlinson-Harashima precoding [11], [12]. Here, we describe the principle idea of the algorithm. For mathematical details, we refer to [1] – [5].

The base station is equipped with n_T transmit antennas, i.e. it can support n_T spatial dimensions. Each user has n_R receive antennas, i.e. it can resolve n_R spatial dimensions. In most cases, we have $n_R < n_T$. The algorithm allocates spatial dimensions successively to users such that in each step the user with the highest SNR is served. In order to determine, to which user the first spatial dimension should be allocated, the SNR for all candidates is computed. If the first spatial dimension was allocated to user i, the base station would form a beam using the right singular vector corresponding to the largest singular value of the channel to user i. The receiver would apply beamforming using the left singular vector corresponding to the largest singular value of the channel to user i. The tap gain of the effective spatial dimension is given by the respective singular value. For the next spatial dimension, it has to be guaranteed that no interference to the already allocated spatial dimension occurs. This is achieved by zero forcing, i.e. we project the channel matrix to a new channel matrix which lies in the null space of the previously allocated spatial dimension. Then, the algorithm tests to which user the second spatial dimension should be allocated in the same way as described before.

The algorithm proceeds accordingly until all n_T spatial dimensions which can be suppported by the base station have been allocated. By doing so, we make sure that successive spatial dimensions do not interfere to previously allocated spatial dimensions. However, there is interference from previously allocated spatial dimensions to later allocated spatial dimensions. This interference is cancelled at the transmitter by means of dirty paper coding, e.g. by Tomlinson-Harashima precoding. In case of OFDM, the algorithm can be run on each subcarrier or resource block. It essentially performs resource allocation in space, time and frequency where the scheduling is done according to the criterion of sum capacity maximization.

IV. Evaluation of CZF-SESAM

For numerical evaluation of multiuser MIMO in the considered large office environment, we used uniform linear arrays (ULA) for both transmitter and receiver. For the transmitter, we chose 4 antenna elements from the transmitter array, for each receiver, we chose two antenna elements from the receiver array. The antenna orientations are indicated by the arrows in Figure 2. We used OFDM with 1024 subcarriers within a bandwidth of 65 MHz.

A. Sum Rate Maximization

First, we consider a scenario where ten users compete for the available resources. Results on the achievable sum capacity are depicted in Figure 7. It is interesting to see that even though CZF-SESAM includes in general suboptimum parts such as zero forcing, the theoretical bound for the sum capacity, the Sato bound [13], can be reached. This is not true for all scenarios, but was also found in many simulations for other scenarios.

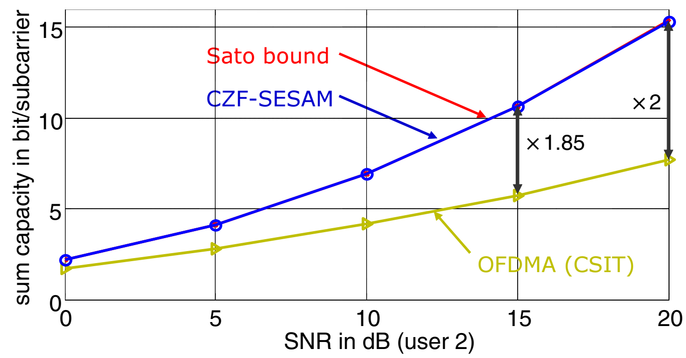

Fig. 7. Sum capacity.

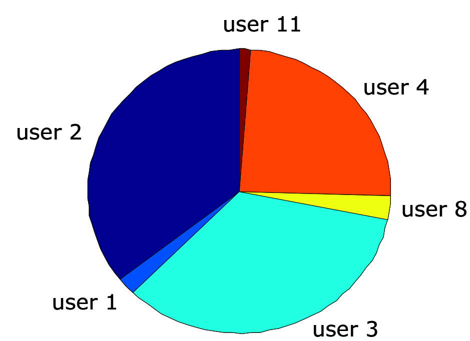

Fig. 8. Rate distribution for sum rate maximizing CZF-SESAM. SNR (reference user 2) = 20 dB

For comparison, we included the sum capacity of dynamic OFDMA according to the middle of Figure 1. CZF-SESAM achieves a gain of a factor 1.8-2 in terms of sum capacity over dynamic OFDMA. This is due to the fact that the maximum number n_T of spatial dimensions can be exploited.

Multiuser diversity aims at maximization of the sum capacity, i.e. the cell throughput. However, it does not include fairness aspects. It can happen that a certain user is not served at all whereas another user gets almost all of the available capacity. The rate distribution for the given scenario is illustrated in Figure 8 for an SNR (reference user 2) of 20 dB where the sum rate achievable by CZF-SESAM is 15.33 bit/subcarrier.

It can be observed that users 2 to 4 get the biggest portion of the cake. As explained in Section II, these users are located within or close to the reverberation distance and have a strong

LOS. Since they are close to the access point, the SNR is high for those users. Hence, CZF-SESAM will favour these users and allocate most of the spatial dimensions to users 2, 3 and 4. Simply put, CZF-SESAM will allocate one strong beam to each of the users 2, 3 and 4.

Interestingly, user 8 is served whereas user 9 is not scheduled at all. From the discussion in Section II, we would expect that user 9 gets an equal or higher share of the available capacity since both users are clearly in the diffuse field and user 9 is a bit closer to the access point. This can be explained as a result of the antenna geometry. We use an uniform linear array which always creates symmetric beams. Since a strong beam is allocated to user 4, there occurs a symmetric beam directed towards user 9 as indicated in Figure 2. Consequently, it is very difficult to serve user 4 and 9 just by spatial separation.

B. Restrictions on Rate Distribution

In order to give a share of the available resources to all users, we have proposed a modification of the CZF-SESAM algorithm [4]. The goal is to obtain a Pareto optimum point on the capacity region while guaranteeing a certain rate ratio between users. Here, we explain only the principle idea. For simplicity, we restrict ourselves to two users. For details, we refer to [4].

The adjustment of allocated resources takes place for each spatial dimension. We consider resource allocation for spatial dimension i. First, we determine the user with the strongest spatial dimension i on each subcarrier. This would be the allocation according to CZF-SESAM. Based on capacity considerations, we then determine the percentage α_k of subcarriers which should be allocated to each user k in order to obtain the desired rate distribution given the current channel state. The respective fraction of subcarriers is reallocated for those subcarriers wich have the smallest difference of the effective singular value for the considered spatial dimension. Then, the next spatial dimension is treated in the same way. Even though this allocation method is heuristic, treating each spatial dimension separately yields an averaging effect. Finally, the desired rate distribution is achieved using proper power loading.

Running this algorithm with the criterion of equal rate for all users significantly reduces the achievable sum capacity. E.g. at an SNR (reference user 2) of 20 dB the sum capacity is reduced to 3.18 bit/subcarrier compared to 15.33 bit/subcarrier without rate restrictions. To further analyze this effect, we look at the situation when only two users compete for the available resources. First, we consider user 1 and user 7. Figure 9 shows the achievable rate distributions. For comparison, we included also the achievable capacity bound [14]. It can be seen that for all rate distributions, the theoretical limit can approximately be achieved using the modified CZF-SESAM algorithm.

On the other hand, the rate distribution for user 4 and user 9 is depicted in Figure 10. In this case, the achievable rate distribution with the modified CZF-SESAM algorithm degrades significantly compared to the capacity bound. This

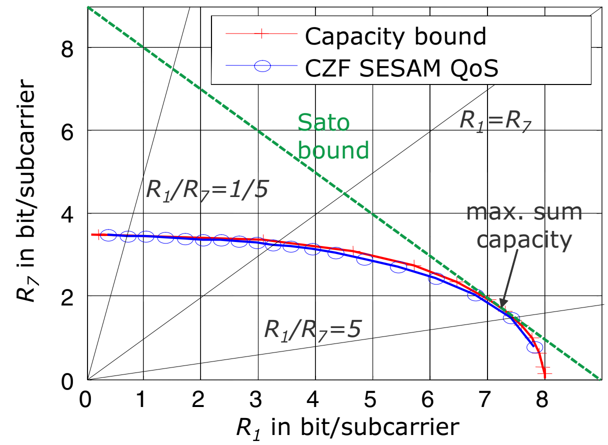

Fig. 9. Rate distribution for users 1 and 7. SNR of user 1: 20 dB

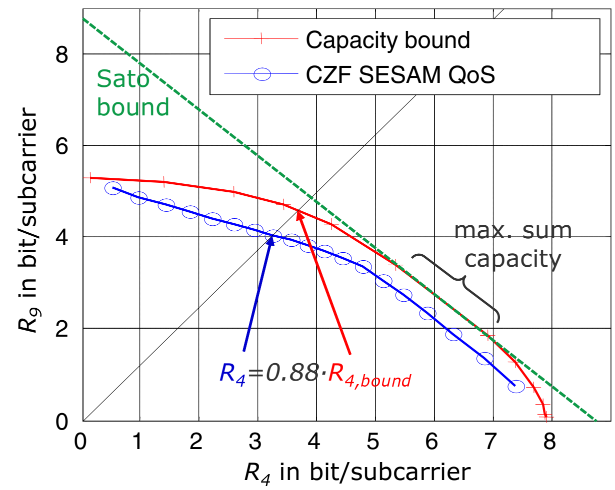

Fig. 10. Rate distribution for users 4 and 9. SNR of user 4: 20 dB

is again due to the symmetrical beam pattern of the applied ULA as explained Section II and Figure 2.

In practical systems with a large number of users and complexity restrictions, we may want to preselect those users which compete for the resources using the CZF-SESAM or its modified extension. It can be concluded from the discussion above that those users should be carefully selected. Users, which are located in positions which are hard to separate spatially given the antenna geometry might rather be separated by means of FDMA or TDMA.

V. Conclusions

We have described an algorithm called CZF-SESAM for resource allocation in a multiuser MIMO-OFDMA system which exploits multiuser diversity. The algorithm has been evaluated based on measured channels in a real world large office scenario rather than with artificial channel models. We have described new results which have been obtained in a measurement campaign. They suggest that even under line-of-sight condition, there is sufficient scattering in order to allow significant MIMO gains as long as the users are located in a distance from the base station where the diffuse field dominates, i.e. the distance of the users from the base station is larger than a reverberation distance. The reverberation distance can be obtained from measurements or it can be easily computed based on room surface and material if the absorption coefficient is known.

Even though CZF-SESAM contains suboptimum ingrediants such as zero-forcing, the algorithm has the potential to achieve the theoretical limit for the sum capacity. We have also extended the algorithm in a heuristic way such that fairness is included in the sense that a desired rate ratio between users is obtained. We have shown that the extended algorithm can get very close to the capacity bound under those restrictions in many scenarios.

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